Hints for New Physics in B_s studies at the Tevatron (CDF and DØ results)

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Motivation

- Search for New Physics in transitions
  $\longrightarrow$ Measurement of the properties of oscillating particles

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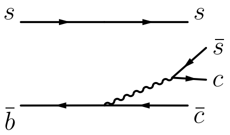
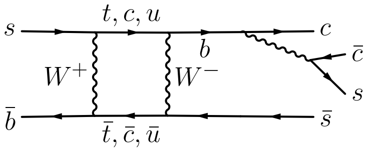
- Now: Measurement of the **mixing phase** β_s
- Accessible through interference of decays with and without mixing

$$B_s \longrightarrow J/\Psi(\rightarrow \mu^+\mu^-)\ \phi(\rightarrow K^+K^-)$$





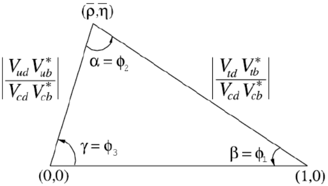
The CKM Matrix

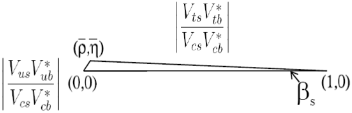
- The Cabibbo-Kobayashi-Maskawa matrix connects mass and weak quark eigenstates

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- To conserve probability, CKM matrix must be unitary.
- Unitary relations can be represented as unitarity triangles.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$





- Subject of this measurement $\boxed{\beta_s^{SM} = arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})}$

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Time evolution of B_s **flavor eigenstates** described by Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} |B_s^0(t)> \\ |\bar{B}_s^0(t)> \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |B_s^0(t)> \\ |\bar{B}_s^0(t)> \end{pmatrix}$$

Diagonalize mass (M) and decay matrices (Γ) $\rightarrow$ **mass eigenstates**:

$$\begin{aligned} |B_s^H(t)> &= p|B_s^0(t)> - q|\bar{B}_s^0(t)> \\ |B_s^L(t)> &= p|B_s^0(t)> + q|\bar{B}_s^0(t)> \end{aligned}$$

Flavor eigenstates differ from mass eigenstates and mass eigenvalues are different. B_s oscillates with frequency $\Delta m_s = m_H - m_L \approx 2|M_{12}|$

CDF	DØ
$\Delta m_s = (17.77 \pm 0.12)ps^{-1}$	$\Delta m_s = (18.56 \pm 0.87)ps^{-1}$

Mass eigenstates have different decay widths:

$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|cos(\phi_s)$ with $\boxed{\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)}$

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Relationship of the Phases

The different phases and their SM expectation value:

$$\phi_s^{SM} = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \cdot 10^{-3} \qquad and \qquad \beta_s^{SM} = arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.02$$

New Physics affects both phases by **same** quantity [1]:

$$\begin{aligned} 2\beta_s^{J/\Psi\phi} &= 2\beta_s^{SM} - \phi_s^{NP} \\ \phi_s^{J/\Psi\phi} &= \phi_s^{SM} + \phi_s^{NP} \end{aligned}$$

If the new physics phase ϕ_s^{NP} dominates over the SM phases $2\beta_s^{SM}$ and ϕ_s^{SM}
$\rightarrow$ neglect SM phases and obtain:

$$2\beta_s^{J/\Psi\phi} = -\phi_s^{NP} = -\phi_s^{J/\Psi\phi}$$

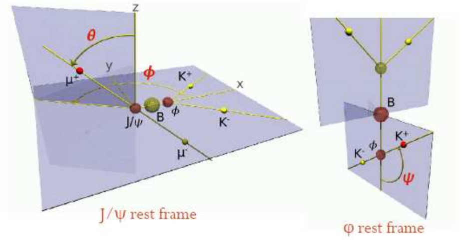
[1] arxiv:0705.3802v2

Decay Topology

B_s	$\longrightarrow$	$J/\Psi\ (\rightarrow \mu^+\mu^-)$	$\phi\ (\rightarrow K^+K^-)$
(spin=0)		(spin=1)	(spin=1)

Conservation of angular momentum lead to three different final states:

L = 0, 2	(s-wave),(d-wave)	CP even
L = 1	(p-wave)	CP odd



Choice of basis:

Transversity basis[a] with corresponding decay amplitudes:

$A_\perp$	CP odd
A_0	CP even
$A_\parallel$	CP even

and angles

$$\vec{\rho} = (\Psi_T, \theta_T, \phi_T)$$

[a] hep-ph/9511363

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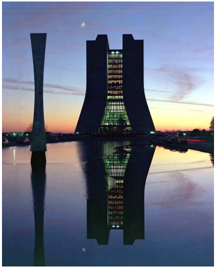
The Tevatron

- Tevatron: circular particle accelerator at the Fermilab (near Chicago, Illinois)
- Proton-Antiproton collisions
- $\sqrt{s} = 1.96\,TeV$
- Two detectors: CDF and D∅



Luminosity / Experiment:

Int. Lumi.	fb^{-1}
delivered	≈ 5.0
on tape	≈ 4.2
this analysis	≈ 2.8

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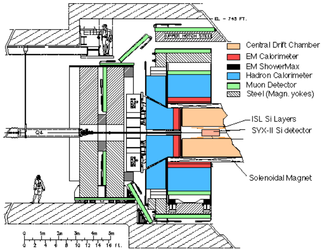
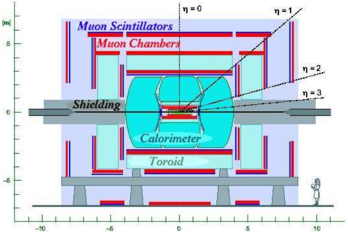
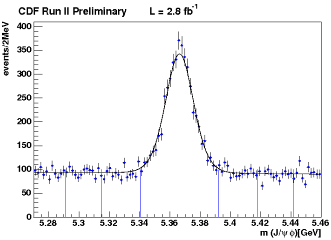
The Detectors

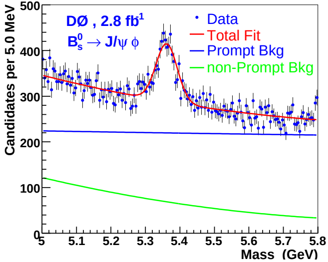
CDF	D∅
▶ Strong tracking system ▶ Good particle identification (dE/dx and TOF)	▶ Large muon and tracking coverage ▶ B field direction reversable
	

Signal Sample

Mixing phase β_s and decay width difference $\Delta\Gamma$ are extracted using an unbinned maximum likelihood fit in

- **Mass**
- Tagging information
- Proper decay time and Transversity angles

<table>
<tr><th>CDF</th><th>D∅</th></tr>
<tr><td>

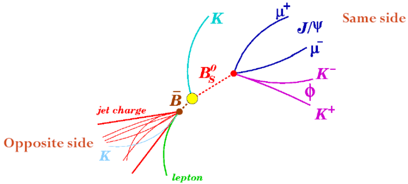
≈ 3200 events
(without PID)</td><td>

≈ 2000 events</td></tr>
</table>

Flavour Tagging

Mixing phase β_s and decay width difference $\Delta\Gamma$ are extracted using an unbinned maximum likelihood fit in

- Mass
- **Tagging information**
- Proper decay time and Transversity angels



Tagging used to increase the sensitivity on the parameters.
Approach:

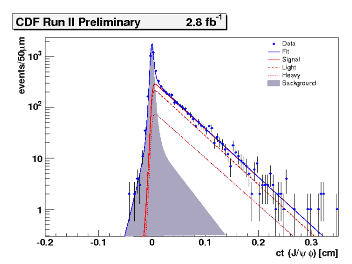
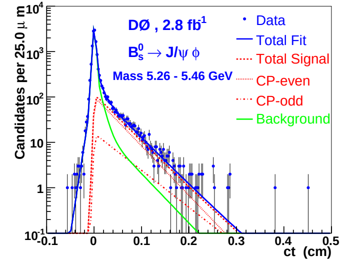
- **OST:** exploits decay products of other b-hadron in the event
- **SST:** exploits the correlations with particles produced in fragmentation

Output: Decision (b or $\bar{b}$) and probability of being correct

Proper Decay Time

Mixing phase β_s and decay width difference $\Delta\Gamma$ are extracted using an unbinned maximum likelihood fit in

- Mass
- Tagging information
- **Proper decay time and Transversity angels**

CDF	D∅
	

CDF: $\tau(B_s) = (1.53 \pm 0.04(stat.) \pm 0.01(syst.))ps$

D∅ : $\tau(B_s) = (1.52 \pm 0.05(stat.) \pm 0.01(syst.))ps$

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Lifetime and Transversity Angels

Time and angular probability for B_s^0:

$$\begin{aligned}
\frac{d^4P(t,\vec{\rho})}{dtd\vec{\rho}} &\propto |A_0|^2 f_1(\vec{\rho})\mathcal{T}_+(t) + |A_{||}|^2 f_2(\vec{\rho})\mathcal{T}_+(t) \\
&+ |A_\perp|^2 f_3(\vec{\rho})\mathcal{T}_-(t) + |A_0||A_{||}| f_5(\vec{\rho})\cos(\delta_{||})\mathcal{T}_+(t) \\
&+ |A_{||}||A_\perp| f_4(\vec{\rho})\mathcal{U}(t) + |A_0||A_\perp| f_6(\vec{\rho})\mathcal{V}(t)
\end{aligned}$$

$$\begin{aligned}
\mathcal{T}_\pm(t) &= e^{-\Gamma t}\left[\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2)\right. \\
&\qquad \left.\mp\, \eta \sin(\Delta m_s t)\ \sin(2\beta_s)\right] \\
\mathcal{U}(t) &= e^{-\Gamma t}\left[\cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right. \\
&\qquad +\eta\cos(\Delta m_s t)\ \sin(\delta_\perp - \delta_{||}) \\
&\qquad \left.-\,\eta\sin(\Delta m_s t)\ \cos(\delta_\perp - \delta_{||})\ \cos(2\beta_s)\right] \\
\mathcal{V}(t) &= e^{-\Gamma t}\left[\cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right. \\
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Explanation

- Angular functions

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Explanation

- Angular functions
- Polarization amplitudes

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- Polarization amplitudes
- Time evolution

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Explanation

- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases
  $\delta_\perp = arg(A_\perp A_0^*)$
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- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases
  $\delta_\perp = arg(A_\perp A_0^*)$
  $\delta_\parallel = arg(A_\parallel A_0^*)$
- Decay width difference

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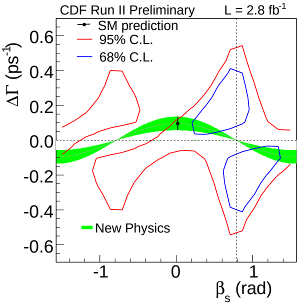
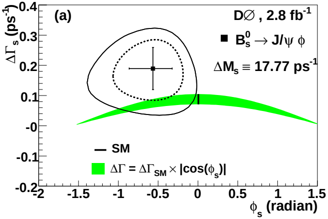
Explanation

- Angular functions
- Polarization amplitudes
- Time evolution
- Strong phases
  $\delta_\perp = arg(A_\perp A_0^*)$
  $\delta_\| = arg(A_\| A_0^*)$
- Decay width difference
- CPV Phase

Results

- Errors of β_s and $\Delta\Gamma$ are not Gaussian $\rightarrow$ study confidence region
- Both experiments show the same tendency

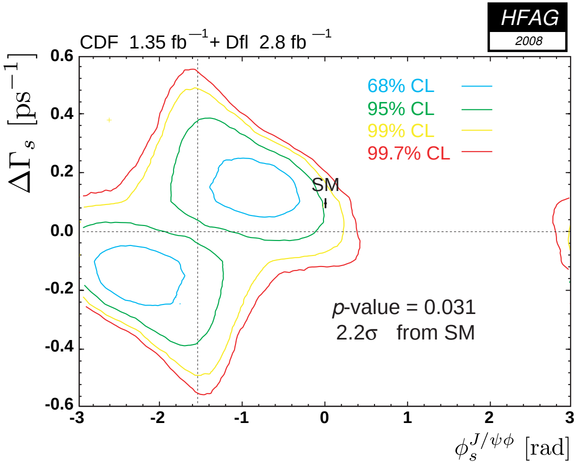
CDF [2]	D∅ [3]
	 (with constraint on strong phase)
$p - value = 7\%$ 1.8 σ from SM	$p - value = 8.5\%$ 1.7 σ from SM

Remember: $2\beta_s^{J/\Psi\phi} = -\phi_s^{J/\Psi\phi}$

[2] http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

[3] http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B08A/

Combination of the up-to-date D∅ measurement with the previous CDF measurement [4]:



$p - value = 3.1\%$

$2.2\ \sigma$ from SM

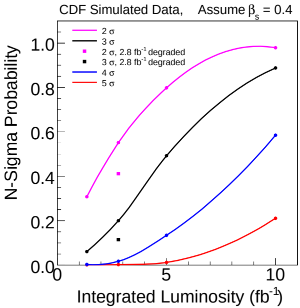
[4] http://hep.physics.indiana.edu/~rickv/hfag/combine_dGs.html

Evolution of the deviation from the SM:

Date	Analysis	Deviation
Dec 2007	CDF (1.35/fb)	1.5 σ
Mar 2008	DØ (2.8/fb)	1.7 σ
Jul 2008	Combination	2.2 σ
Jul 2008	CDF (2.8/fb)	1.8 σ

Fluctuations? Maybe! But the coherent pattern is interesting!

Probability to observe a non-SM β_s at CDF:



Conclusions and Future Plans

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- Measurements of CPV in B_s system done by both CDF and D∅

Future Plans:

Conclusions:

- Measurements of CPV in B_s system done by both CDF and D∅
- Study confidence region in $\Delta\Gamma$-β_s plane

Future Plans:

Conclusions:

- Measurements of CPV in B_s system done by both CDF and D∅
- Study confidence region in $\Delta\Gamma$-β_s plane
- Both CDF and D∅ observe 1-2 σ deviations from SM predictions

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Conclusions and Future Plans

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- CDF: Improvements in Tagging and PID

Thanks for your Attention

and

Stay tuned for Updates!

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Angular Functions

$$
\begin{aligned}
f_1(\vec{\rho}) &= 2cos^2\Psi_T(1 - sin^2\theta_T cos^2\phi_T) \\
f_2(\vec{\rho}) &= sin^2\Psi_T(1 - sin^2\theta_T sin^2\phi_T) \\
f_3(\vec{\rho}) &= sin^2\Psi_T sin^2\theta_T \\
f_4(\vec{\rho}) &= -sin^2\Psi_T sin2\theta_T sin\phi_T \\
f_5(\vec{\rho}) &= 1/\sqrt{2} sin2\Psi_T sin^2\theta_T sin2\phi_T \\
f_6(\vec{\rho}) &= 1/\sqrt{2} sin2\Psi_T sin2\theta_T cos\phi_T
\end{aligned}
$$

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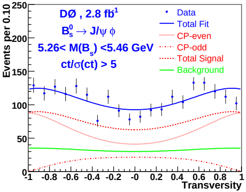
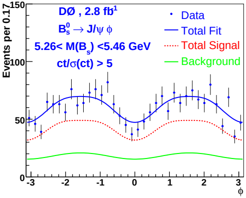
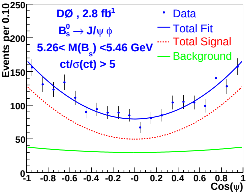
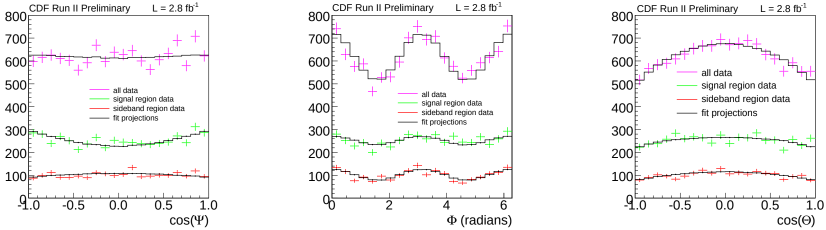
DØ : Angular Projections



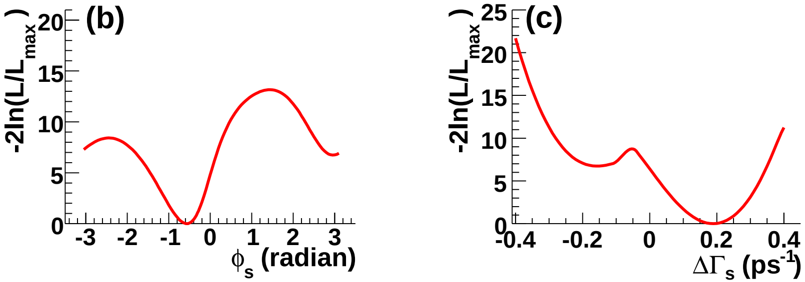




CDF: Angular Projections



DØ : Likelihood Scan



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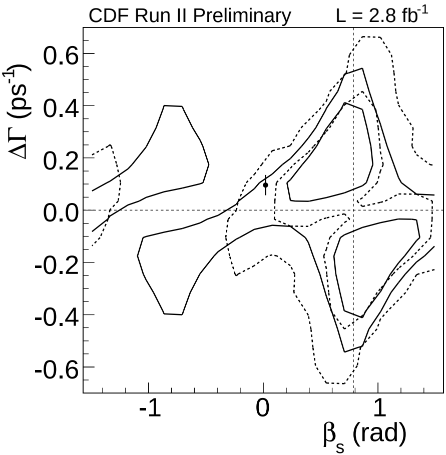
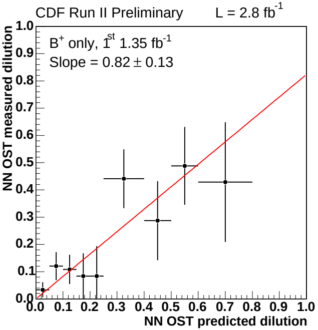
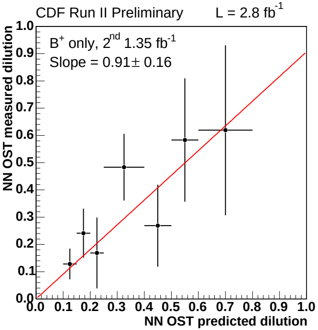
CDF: 2D likelihood profile comparison with published result



CDF: OST in B^+

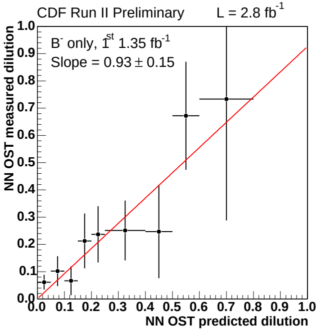


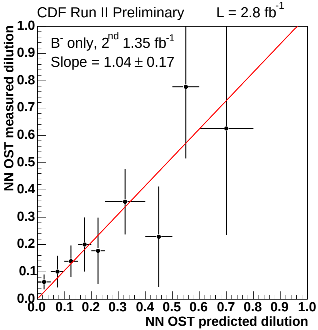
CDF Run II Preliminary
L = 2.8 fb-1
B+ only, 1st 1.35 fb-1
Slope = 0.82 ± 0.13
NN OST measured dilution
NN OST predicted dilution
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



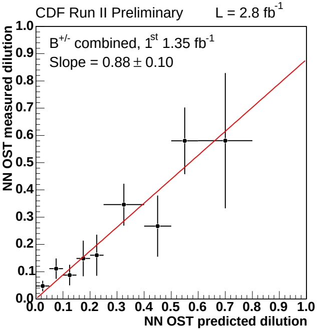
CDF Run II Preliminary
L = 2.8 fb-1
B+ only, 2nd 1.35 fb-1
Slope = 0.91± 0.16
NN OST measured dilution
NN OST predicted dilution
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

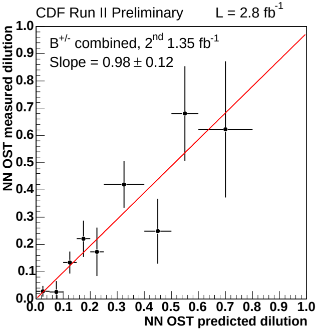
CDF: OST in B^-


CDF Run II Preliminary
L = 2.8 fb-1
B- only, 1st 1.35 fb-1
Slope = 0.93 ± 0.15
NN OST measured dilution
NN OST predicted dilution

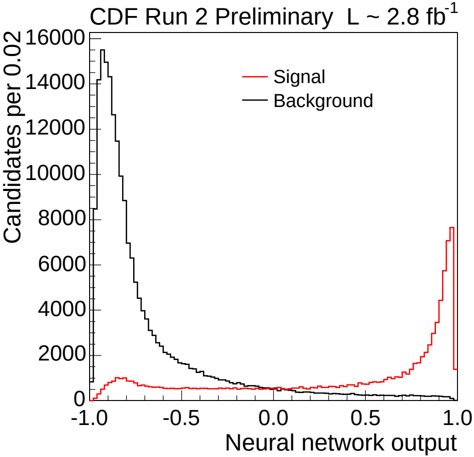

CDF Run II Preliminary
L = 2.8 fb-1
B- only, 2nd 1.35 fb-1
Slope = 1.04 ± 0.17
NN OST measured dilution
NN OST predicted dilution

CDF: OST in $B^{\pm}$

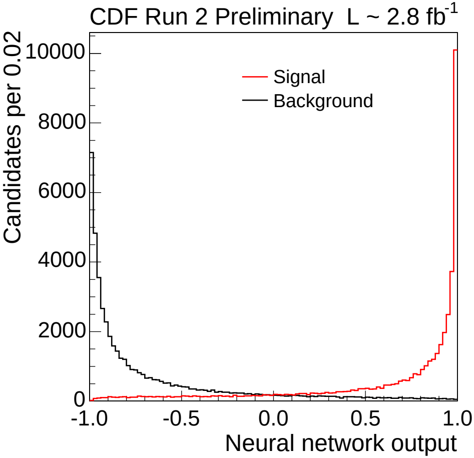




CDF: Neural Network for $B^{\pm}$



CDF: Neural Network for B_s



CDF: Invariant Mass of B^+